Demonstration and characterization of a multibillion-shot, 2.5-mJ, 4-ns, *Q*-switched Nd:YAG laser

J. L. Dallas, R. S. Afzal, and M. A. Stephen

We have demonstrated and characterized a *Q*-switched Nd:YAG laser under continuous operation for over 7 billion shots. Through periodic monitoring of the laser's vital signs, the system dynamics were decoupled to identify the sources of degradation. The initial and the final pump-laser diode wavelengths and powers were measured and compared. No evidence of an accumulative effect leading to optical damage at a fluence lower than the single-shot threshold was observed.

Key words: Accumulative exposure, optical damage, laser diode lifetime.

1. Introduction

As part of NASA's suite of Earth Observing Satellites, Goddard Space Flight Center is developing a laser altimeter for measuring the dynamics of the polar ice sheet mass balance.[1] This Geoscience Laser Altimeter System (GLAS) requires a diode-pumped, *Q*-switched Nd:YAG laser transmitter producing 150-mJ, 4-ns pulses at a 40-Hz repetition rate in a single transverse mode. The mission lifetime goal is 5 years (6.3 billion shots). The laser design must satisfy the instrument requirements while balancing the constraints of high efficiency, light weight, small size, proven reliability, and long-duration operation in the space environment. Upon selection of a laser design, the projected performance of the GLAS laser can still be limited by a number of system degradations. Two of the most immediate concerns are optical damage to the components caused by their interaction with the intense intracavity laser fluence and degradation of the pump-laser diodes. Over the past 30 years, substantial effort has been devoted to understanding the sources of optical damage. In addition, the average damage threshold has increased through advanced materials research and improved fabrication techniques and processes.[2] Yet to our knowledge, no data describing the multibillion-shot accumulative-exposure effect that *Q*-switched 4-ns pulses have on intracavity optical components exist.[3] It has been theorized that the multishot damage threshold is significantly lower than the single-shot threshold.[4] Multibillion-shot survivability is critical to NASA's stringent lifetime requirements as well as commercial laser vendors seeking lower maintenance products. In addition, relatively little lifetime data exist for high-power pump-laser diode arrays. These issues must be investigated, and their impact incorporated into the laser design.

Rather than addressing the many technical concerns separately, a system approach was taken to encompass many of the coupled characteristics of the laser transmitter simultaneously. A test of the actual GLAS laser breadboard is the most direct procedure. Although this approach complicates the extraction of detailed component knowledge in the case of failure, an existence proof demonstrates the compatibility of the components and the feasibility of our system architecture. At present, the baseline design incorporates an oscillator–amplifier configuration. Our highest level of concern is with the oscillator, in part because of the large intracavity fluences, unknown diode-pump lifetimes, mirror tolerances, and electro-optic switches. Therefore as an initial test the oscillator alone was investigated.

To obtain multibillion-shot results in a reasonable time, an accelerated-repetition-rate (500-Hz) version of the GLAS oscillator[5,6] was built with modifications only to the thermal management to account for the higher average power. An Accelerated GLAS Exposure Station (AGES) was developed to monitor the

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laser's vital signs autonomously.[7] The power, pulse width, beam size, laser diode drive current, coolant temperature, and Q-switch drive voltage were recorded throughout the experiment. Each diagnostic instrument was periodically read by a computer. Upon analysis of the stored data, the system dynamics were decoupled to identify the sources of degradation. The initial and the final pump-laser diode wavelengths and powers were measured and compared. Over 7 billion shots were accumulated during AGES's nonstop 5.5-month operation.

2. Accelerated GLAS Exposure Station

Figure 1 shows the AGES layout. The output from the Nd:YAG laser was split into three beams. The laser's power, pulse width, spatial profile, laser diode drive current and pulse width, Q-switch drive voltage, and water-coolant temperature were recorded as a function of the number of laser shots. Given the time required for this experiment and the volume of data, all the laboratory instruments were interfaced to a 486-based computer running LabView. Each diagnostic instrument was automatically read every 30 min (900,000 shots). The laser and sensors were assembled and operated on an optical bench under a laminar flow to reduce the number of airborne particulates. No extreme measures were taken to ensure cleanliness in the operating environment.

The laser was optically pumped by an SDL-3255-C1 100-W quasi-cw laser diode bar. Its highly diverging light was focused with a 1-mm-diameter glass rod located approximately 300 μm from the diode mount. The diode was water cooled by a Neslab CFT-33 circulating chiller. The diode's initial emission wavelength was centered at 808 nm with a FWHM linewidth of 1.6 nm under the following conditions: 26 °C coolant temperature, 118 A of drive current, a 200-μs drive pulse width, and a 500-Hz repetition rate. This 10% duty cycle is 2.5 times the vendor's recommended value.

The Nd:YAG slab was fabricated with uncoated Brewster faces and provided a seven-bounce zigzag path through the medium. Its mount was water cooled in series with the laser diode. A Cleveland Crystal KD*P Pockel cell with sol-gel-coated end faces was used to Q switch the laser. It was driven with 3-kV pulses provided by a pair of Analog Modules 820-49/50 drivers. The optical switching rise–fall time was measured to be 16 ns. The 10-cm resonator was formed by a 2.5-m radius-of-curvature high reflector and a 60% reflecting output coupler provided by CVI-West. No specialized parts were used other than the pump diode, which was specified to lase at 808 nm at 500 Hz.

At the start of this test, over 2.5 W average power (long pulse) was obtained in a 400-μm $1/e^2$-radius mode when the diode was pumping at 500 Hz and 200 μs. Q-switching yielded 1.25 W average power with 4.5-ns pulses, or 2.5 mJ/pulse. The Gaussian-like spatial profile showed little repetition-rate dependence up to 500 Hz. An M^2 of 2.1 was measured. Two to three longitudinal cavity modes were observed, and their mode beating effect could be seen in the temporal pulse shape. The diode drive current was decreased to 110 A before the performance test was initiated.

Figure 2 shows the laser energy, pulse width, and water temperature as a function of the number of shots. The water temperature oscillated approximately ±2.5 °C on roughly an 11.6-day cycle. These temperature changes moved the diode emission wavelength around the Nd:YAG peak absorption spectrum. The effect of the water-temperature oscillations can be seen in the energy output of the laser. In addition, the diode center emission wavelength at a given temperature increased over the life of the experiment (Fig. 3). This caused the temperature-cycling effect to be more dramatic as the center wavelength translated further off the peak Nd:YAG absorption wavelength. After 5 billion shots, algae were visible in the water-cooling lines. The algae restricted flow through the diode coolant lines and possibly lowered the thermal conductivity of the diode-mount–water interface. At the end of the experiment, the laser diode heat sink was dissected. Under a microscope, green corrosion coating all the cooling-channel walls was visible. The material composition of this corrosion is being investigated.

The diode's output energy decayed by 22.8% over 7 billion shots. The decreasing gain in the laser

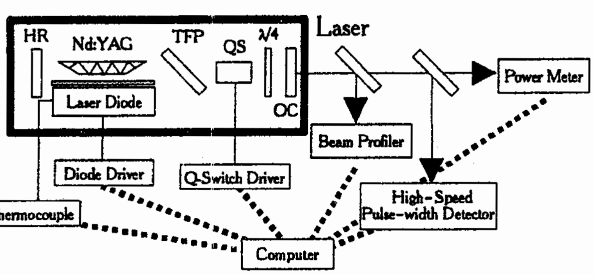

Fig. 1. Schematic of Accelerated GLAS Exposure Station (AGES). HR, high reflector; TFP, thin-film polarizer; QS, Q switch; OC, output coupler.

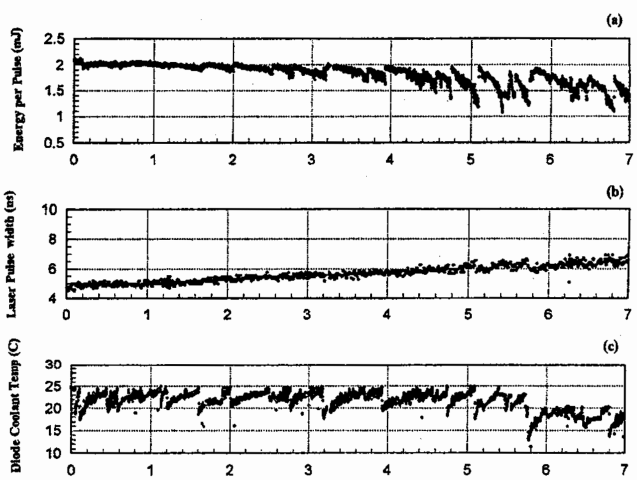

Fig. 2. AGES results: (a) energy per pulse versus shots, (b) laser pulse width versus shots, (c) coolant temperature versus shots.

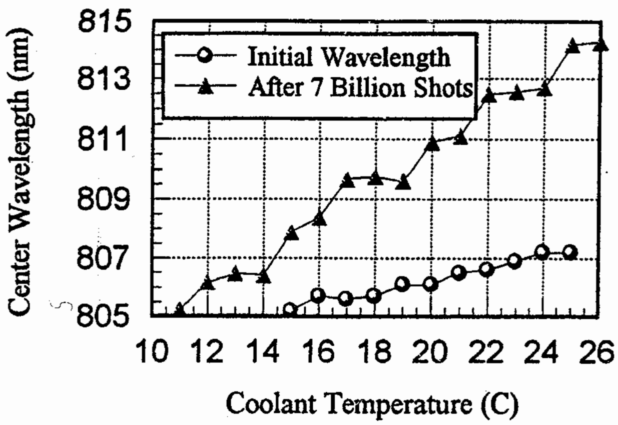

Fig. 3. Temperature tuning of the pump-laser diode.

caused the laser pulse width to increase slowly. In a separate experiment, a stack of three SDL-3255 100-W operation. Quasi-cw bars were life tested at 200 Hz and 200 μs. After 5 billion shots, the total power from all three bars had degraded by 20%.[8]

Other than the effects attributed to the diode pump wavelength and energy, there were no other changes over the AGES 7-billion-shot experiment. The Nd:YAG crystal, Q-switch, optics, and all drivers operated identically to their initial performances. At the end of the experiment, the cavity components were realigned to ascertain if mechanical drift was responsible for the power drop. No additional energy or shortening of the pulse width was observed. Visual inspection of the optics showed no signs of optical damage. The high reflector and output coupler mirrors were subsequently tested by Spica Technologies to determine their damage threshold. The high reflector's threshold was 8 J/cm^2, and the output coupler's was 23 J/cm^2. The laser's intracavity fluence was calculated from

$$\text{Intracavity Fluence} = \frac{2\left(\dfrac{1+R}{1-R}\right)E_{\text{out}}}{\pi r^2},$$

where R is the output coupler reflectivity, E_{out} is the output energy per pulse, and r is the $1/e^2$ intracavity beam radius. The factor of 2 comes from the peak-to-average difference when a Gaussian spatial distribution is assumed. An intracavity fluence of 4 J/cm^2 was calculated. Within the slab, an additional factor of 2.7 accounts for the peak interference of the counterpropagating beams at the total internally reflected faces and the increase in the spot size from the Brewster face. There was no evidence of an accumulative effect leading to optical damage at a fluence lower than the single-shot threshold.

3. Conclusion and Future Directions

An existence proof was conducted, demonstrating that a diode-pumped, Q-switched laser with an intracavity fluence of 4 J/cm^2 and an intensity of 900 MW/cm^2 could survive 7 billion shots. Though this one test is surely not a statistically significant sample, it does provide a previously nonexistent data point for the accumulative-exposure survivability of optical components under these conditions. More important, it demonstrates the feasibility of this laser oscillator design in the laboratory for the GLAS program. The diode pump was the limiting component in the system. Its output power degradation was expected, but the wavelength translation was not. Though the algae were most likely the cause of the diode center-wavelength translation, the effects of a diode's age on its wavelength emission require further study. From an understanding of the Nd:YAG's laser performance characteristics over the shot count of a 5-year mission, our optimum laser can be designed. This experiment was stopped after 7 billion shots were accumulated. AGES will be upgraded and used as a billion-shot tool as part of a more comprehensive optical component qualification procedure for selecting vendors and materials to provide the flight components for the GLAS program.

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